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ORIGINAL ARTICLE

The impact of local wind and spatial conditions on geometry blade of wind turbine

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Abstract

The research addresses the pressing need to understand wind conditions for optimal wind energy utilization, a crucial aspect of achieving global energy sustainability. While previous studies have focused on assessing wind energy potential and terrain roughness, gaps persist in understanding how wind and spatial conditions affect blade geometry. Therefore, this study aims to investigate the impact of local wind conditions on wind turbine blade geometry, integrating nonuniform wind inflow due to wind shear into the theoretical model. Through the paper, it explores blade design for varying inflow conditions and analyses the relationship between terrain type and blade designs. A novel approach to wind turbine blade design, utilizing a theoretical model that combines the local momentum theorem with insights from propeller vortex theory was adopted. Through the analysis, the authors demonstrate that variations in terrain significantly influence blade geometry, underscoring the necessity for tailored turbine designs based on local conditions. The findings reveal discrepancies in blade geometry across different turbine capacities and terrain types, offering novel insights into wind turbine performance optimization. By tailoring blade geometry to specific locations enhances resource utilization, offering insights for energy policymakers. The research provides validated methods for optimizing turbine geometric parameters, opening avenues for increased local investment in wind energy and promoting distributed energy development. Illustrated with wind plants examples, the paper concludes by outlining future research directions in this field.

KEYWORDS

annual average wind speed, blade geometry design, energy efficiency, wind energy, wind shear

1 | INTRODUCTION

The global demand for energy and sustainability are paramount in the 21st century.[1] Wind energy emerges as a viable alternative to fossil fuels, driving energy sustainability.[2] Wind energy generates electricity, offering a promising avenue for clean and secure distributed wind energy.[3,4] The wind turbine provides an economical and environmentally friendly energy conversion system.[5] To comprehend energy sustainability, measures encompass energy conservation, increased efficiency, and greater reliance on renewable energy sources,[6–8] leading to environmental enhancements and reduced carbon dioxide emissions,[9,10] while boosting technological advancement, energy security, and socioeconomic growth.[11–17] Recent literature has emphasized emerging trends in energy research, particularly in focus on wind energy[18–21]

For optimal energy of wind utilization is crucial understanding wind conditions at the dedicated location. Therefore, investigating the impact of local wind and spatial conditions on turbine energy efficiency is essential. This involves analyzing the relationship between wind speeds, terrain roughness, and electricity generation by selecting the geometry of the wind turbine blade.

Studies assessing wind energy potential[9] (Şahin & Türkeş, 2020) and specific locations[22–25] are of substantial interest. Numerous studies have harnessed the Weibull distribution function to investigate wind resources across diverse global regions. For instance, researchers have applied it to analyze wind characteristics in Morocco,[23] Iraq,[22] Iran,[25] Pakistan,[24] and China's southeastern coast.[26] Hussain et al.[27] employed four numerical methods for estimating Weibull parameters. Additionally, terrain roughness plays a pivotal role in assessing wind conditions, with studies examining its impact in various contexts, including semiurban areas,[28] Romania,[29] and the west coast of Turkey.[30] This research uses the Weibull distribution as the theoretical location of the wind turbine. Analyzing the presented part of the literature, the researchers' questions arose, presented in Table 1. This resulted in the analysis of the next part of the literature.

Research has focused on blade geometry in alignment with the blade element momentum theory (BEM), involving calculations of aerodynamic coefficients along the blade length[31] and the coupling of multiobjective algorithms with BEM for blade design.[32] A shadow effect analysis of wind turbine towers using a combined potential flow and BEM model was presented by Ghandour et al.[33] While much of the analyzed work has centered on blade design methods under homogeneous flow conditions, there is also notable research addressing rotor design under inhomogeneous flow caused by the vertical wind speed profiles.[31,34–39] For instance,[31] pioneered blade design using the blade element angular momentum theory, investigating the impact of wind shear on the designed blade through power law modeling of wind shear. In the study by Akour et al.,[40] the authors explored the impact of wind profiles in two locations within the United Arab Emirates. They empirically tested a theoretical model and conducted an economic analysis for the project. Conversely,[31] delved into the influence of wind speed profiles on aerodynamic properties and energy production, employing BEM theory for designing wind turbine blades. These findings highlight potential research gaps worth exploring. There are no answers to the questions posed in Table 1 related to the analyzed literature. None of the referenced literature items change the combination of wind turbine blade design with presenting variations of geometry of blade wind turbine across different locations in terms of average annual speed and terrain roughness considering wind shear.

The aim of the article is to examine the impact of local wind conditions on wind turbine blade geometry, integrating nonuniform wind inflow due to wind shear into the theoretical model. The research is achieved by presenting a relationship between the location of a wind turbine and the geometry of the turbine blade, considering in the theoretical model of wind the nonuniform wind inflow caused by the wind shear. In response, the authors focus on distributed wind energy generation and its geographical utilization. But this research goes beyond

TABLE 1 Research inquires and their corresponding sections.

No.	RQs	Sections they pertain to	Methods
1	Does taking wind shear into account affect the geometry of wind turbine blades?	3	The friction coefficient α from Hellman exponent and BEM theory and vortex theory
2	Is there a relationship between the location of the turbine in different locations with different terrain roughness and the geometry of the wind turbine blades?	3	Hellman exponential law and BEM theory and vortex theory

Abbreviation: BEM, blade element momentum.

Source: Own elaboration.

fundamental analyses by exploring the impact of local wind and spatial conditions on optimizing wind turbine blade design into account wind shear. Comparisons with existing literature, such as Akour et al.[40] and Kavari et al.[31] highlight advancements in blade design tailored to specific locations, surpassing previous studies. Moreover, the research used an original approach to the design of a wind turbine blade (Table 1, the last column).

To fill these gaps, the study investigates the impact of local wind conditions on wind turbine blade geometry, specifically integrating nonuniform wind inflow due to wind shear into the theoretical model (Section 2.2.1). By analyzing the relationship between turbine location and blade design while considering wind shear effects, the research aims to advance our understanding of wind turbine optimization for diverse geographical settings. The theoretical model (Section 2.2.2) used in design is based on a combination of the local momentum theorem and the use of the results of the propeller vortex theory.

To illustrate our approach, wind power plants of different nominal power were used as demonstrative case studies. This paper aims to make a new insight and contribute to the discourse surrounding the influence of wind characteristics on energy efficiency.

The study's approach builds upon existing literature, showcasing advancements in blade design methodologies tailored to specific locations. By addressing these research gaps, the study contributes to enhancing wind energy generation efficiency and promotes the development of distributed wind energy systems.

- Given the identified gaps, the primary novelties of this study are as follows: Application of an enhanced abductive research approach, uniquely combining theoretical understanding and practical implications, to address gaps in renewable energy literature;
- Emphasis on the intricate interplay between local wind conditions, terrain roughness, and blade geometry while considering the vertical wind profilecontributing to a holistic understanding of wind turbine performance and providing a unique contribution to the broader discourse on renewable energy development.

The paper's workflow consists of the following sections (Figure 1) inspired by the studies[41,42]:

- Section 1: Defining practical relevance to identify problem and corresponding research gap and research questions. Conducting literature review to highlight the need of the research.
- Section 2: Describing theoretical localization methods for wind power plant as well as methods used for designing blades.
- Section 3:
- Presentation of research results aimed at:

(a) development of a theoretical wind model considering wind shear,
(b) finding dependencies between the terrain roughness and the geometry of wind turbine blade considering nonuniform wind inflow.

- Highlighting findings and illustrating practical and theoretical implications.
- Section 4: Conclusion.

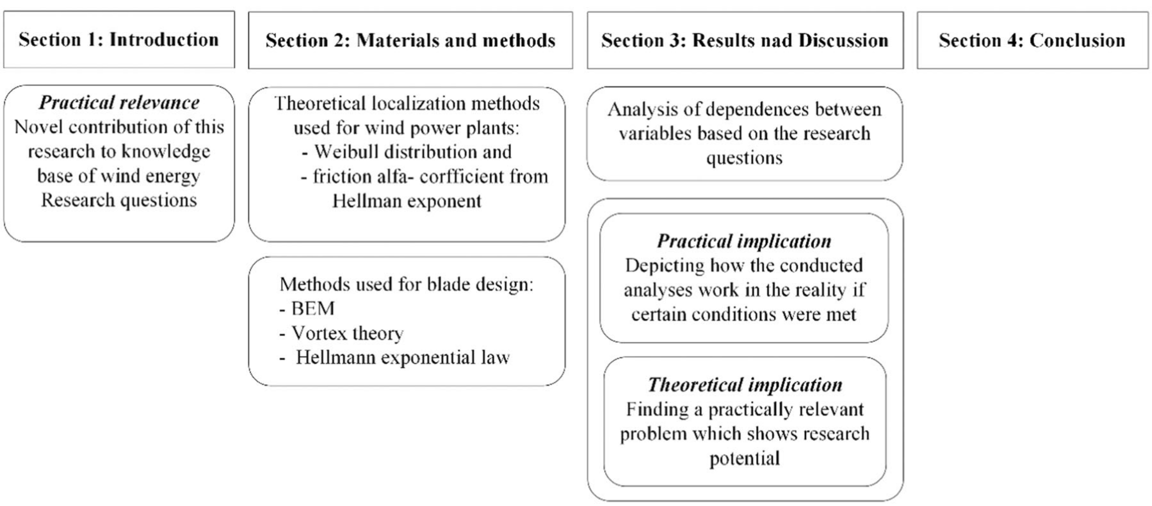

FIGURE 1 The elements of paper workflow. *Source*: Own elaboration.

2 | MATERIALS AND METHODS

2.1 | Methods for estimation of theoretical localization

Wind speed is a stochastically changing quantity and can only be characterized statistically. The basic parameter that characterizes a quantity changing in a random manner is its average value over time. A preliminary evaluation of conditions for investing in the construction of a wind power plant in a specific area is conducted based on maps of average annual wind speeds. The definitive evaluation of wind conditions should be carried out based on measurements obtained at the site (or sites) where the investor intends to establish the power plant.

More accurate insight into the behavior of a stochastically changing quantity is provided by its distribution law. Wind speed, as a random process, is well approximated by the Weibull distribution. The probability distribution of wind speed at a particular location can be described using a two-parameter Weibull probability distribution function. The two-parameter Weibull distribution is considered a valid model and is extensively used in the wind energy sector.[43,44] However, it is important to note that the actual distributions in a given site and year may differ significantly (up to 30%) from that calculated based on the Weibull distribution. Jung and Schindler[45] reviewed studies published between 2010 and 2018 that compared the fitting probability of various theoretical parametric distributions. The authors this paper found that the two-parameter Weibull distribution was the most frequently evaluated distribution.

The Weibull probability density function is defined as follows (Equation 1):

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right], \quad (1)$$

where: v is the wind speed in m/s; $k > 0$ is the dimensionless shape parameter; $c > 0$ is the scale parameter in m/s.

Another parameter that determines the location is the friction coefficient α (Equation 2). Table 2 shows the friction coefficients of various land spots that, in each case, are given in function of the land roughness. For further calculations, the averaging time of the measurements was assumed to be 10 min.

2.2 | Methods used for designing wind turbine rotor in different localization

2.2.1 | Method for defining wind speed distributions on different altitude

The real wind turbine works in the Earth's boundary layer. This circumstance leads to the situation in which the inflow on rotor of HAWT is nonuniform, according to the vertical velocity distribution. The friction between the land's surface and moving air generates a spatial wind speed profile, where average annual wind speeds increase with altitude. Among the simpler expressions used to describe this phenomenon, the Hellmann exponential law is commonly employed. This

TABLE 2 Friction coefficient α for a variety of landscapes based on Fernandez and colleagues.[46–48]

Terrain roughness class	Description of the terrain	α for the averaging time 1 h	α for the averaging time 10 min	α for the averaging time 2 min	α for the averaging time 2 s
0	Flat, open terrain where the height of unevenness is less than od 0.5 m.	0.150	**0.130**	0.115	0.075
1	Flat, open or slightly undulating terrain. Single buildings or trees	0.165	**0.140**	0.120	0.075
2	Flat or undulating terrain with open spaces. Groups of trees or low buildings.	0.190	**0.155**	0.125	0.080
3	Forested areas, suburbs of larger cities and small towns, sparsely built-up industrial areas.	0.220	**0.170**	0.135	0.080
4	Area with numerous obstacles located at a short distance, that is, clusters of trees, buildings at a minimum distance of 300 [m] from the place of observation.	0.270	**0.200**	0.150	0.085
5	Terrain with numerous large obstacles located close to each other, forest areas, centers of large cities.	0.350	**0.245**	0.175	0.085

law establishes a correlation between wind speed measurements at two different heights and is mathematically represented by the Equation (2):

$$\boldsymbol{v}(\boldsymbol{h}) = \boldsymbol{v_m}\left(\frac{\boldsymbol{h}}{\mathbf{10}}\right)^{\alpha}, \tag{2}$$

where: $\boldsymbol{v_m}$ is the wind speed at $h = 10$ m (m/s); $\boldsymbol{h}$ is the height above ground surface (m); $\boldsymbol{\alpha}$ is the factor depending on the type of terrain.

The height of point b from the rotor axis is calculated from the formula:

$$h_b = h + r \cdot \cos\psi, \tag{3}$$

where ψ is the blade azimuth.

The height of the blade element and azimuth angle markings are shown in the Figure 2. Considering Equations (2) and (3), it is possible to determine the formula for the wind speed at height h_b:

$$v(h_b) = v(h) \cdot \left(\frac{h + r\cos(\psi)}{h}\right)^{\alpha}. \tag{4}$$

The power law (Equation 4) can be presented in a polar coordinate system related to the rotor axis:

$$v(r,\psi) = v(h) \cdot \left(\frac{h + r\cos(\psi)}{h}\right)^{\alpha} = v(h)[1 + W_s(r,\psi)], \tag{5}$$

where $W_s(r,\psi)$ is a function of the wind speed profile, which we can approximate using the Taylor series:

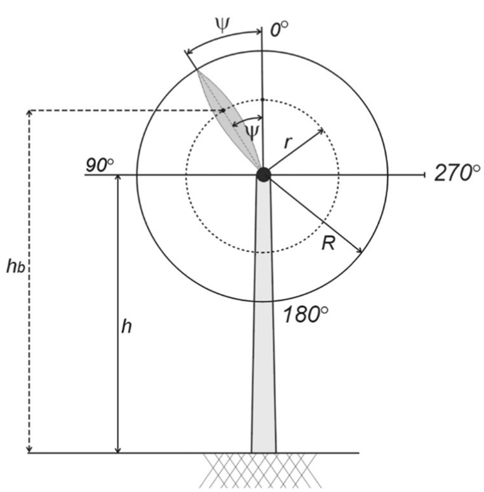

FIGURE 2 Azimuth angle and height of the blade element. *Source*: Own elaboration.

$$W_s(r,\psi) = \alpha\frac{r}{h}\cos\psi + \frac{\alpha(\alpha-1)}{2}\left(\frac{r}{h}\right)^2\cos^2\psi + \frac{\alpha(\alpha-1)(\alpha-2)}{6}\left(\frac{r}{h}\right)^3\cos^3\psi. \tag{6}$$

In the further part of our considerations, we will limit ourselves to only the 1st part of the Equation (6):

$$W_s(r,\psi) = \alpha\frac{r}{h}\cos\psi. \tag{7}$$

After taking into account the relationship (Equation 7) in Equation (5), the velocity profile along the rotor radius depending on the height is represented by the formula:

$$v(r,\psi) = v(h)\left[1 + \alpha\frac{r}{h}\cos\psi\right]. \tag{8}$$

Figure 3 shows the speed fluctuations for individual elements of the rotor blade, calculated based on formula (8). There are significant differences between these fluctuations for different coefficients α.

2.2.2 | Method for defining of blade geometry

The power contained within the airflow increases exponentially with the third power of wind speed and linearly with the increase in rotor size. Thus, it holds great importance to position a wind turbine at a site with the most favorable wind conditions. Moreover, once the site is selected, the significance of the rotor area becomes evident. Over several decades, there has been a consistent increase in rotor size. With the increasing rotor size, the design and manufacturing aspects of wind turbine rotor blades become important. The final shape of blade involves a trade-off of many factors, such as: aerodynamic loads, efficiency, manufacturing costs, aeroelastic stability, and fatigue loads. Recognizing that the expenses incurred in blade manufacturing account for about 10% of the total wind turbine cost, investments in innovative blade design, manufacturing methods, and materials are well-justified. A well-designed blade allows reducing the demands on the hub and tower, cutting down the cost of manufacturing and operating a wind turbine, and impacting the efficiency of energy production. Through the application of the thrust distribution of a rotor rotating in an optimized vertical wind speed profile using theoretical model analyzed the influence of speed profile and terrain roughness on wind turbine blade geometry. The theoretical model applied in this study, thus in design problem, based on local momentum theorem[32] employs some results of the vortex theory of propellers.[49,50] The new model proposed by the

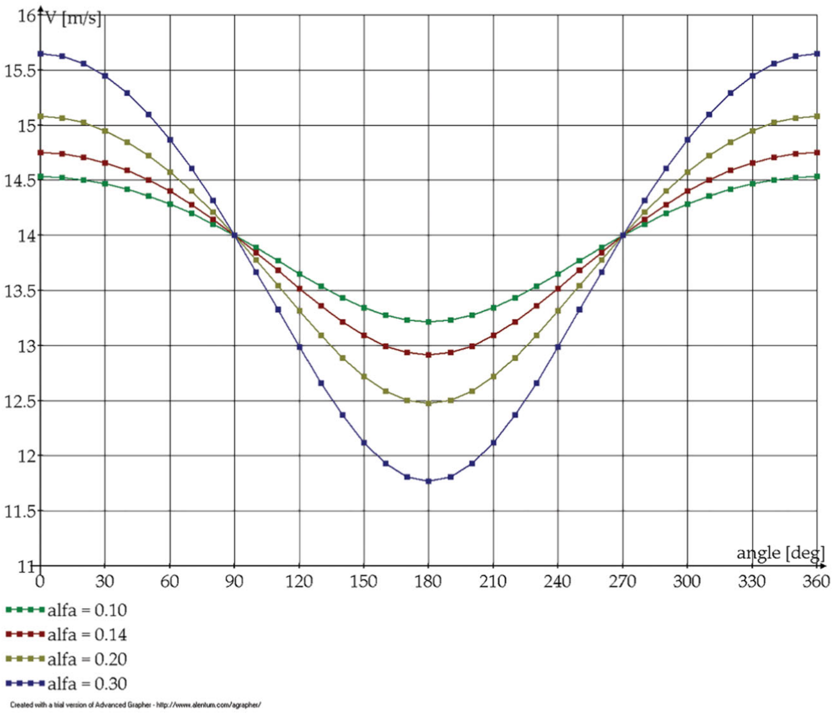

FIGURE 3 Wind speed fluctuations for individual blade elements. *Source*: Own elaboration.

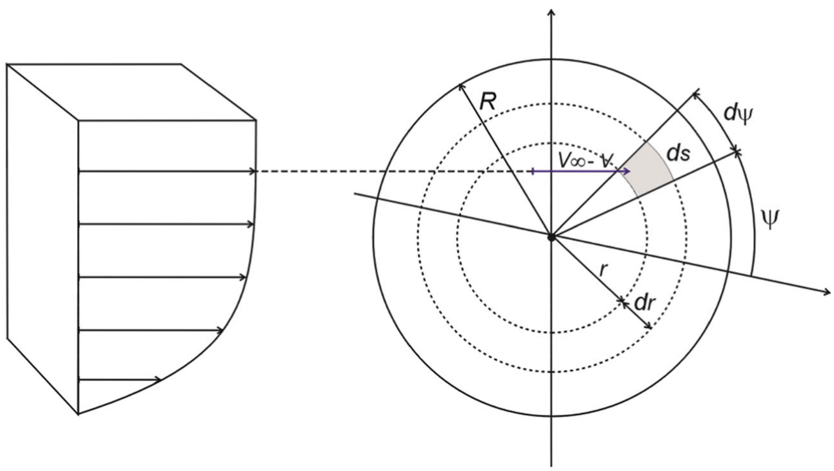

FIGURE 4 Non uniform inflow at actuator disk. *Source*: Own elaboration.

authors combines both of these methods to design blade of wind rotor.[51,52] The authors presented the distribution of the thrust force of a rotor rotating in a vertical wind speed profile optimized using the extended momentum theory.

The local thrust force for a single segment is equal presented by Figure 4. Explanations of the symbols shown in Figure 4 and in the formulas below are presented in Table 3.

The total ideal thrust and power are equal, respectively:

$$dP_x = \iint_S 2\rho v(V_\infty - v)rdrd\psi, \tag{9}$$

$$N = \iint_S 2\rho v(V_\infty - v)^2 rdrd\psi. \tag{10}$$

The problem of the optimal resistance distribution (change of momentum) of the rotor working in the vertical speed profile. It can be presented as follows: we assume a constant power of N_0, and we look for thrust. Using the above equations, we write the Hamiltonian:

$$H = 2\rho v(V_\infty - v) - \lambda_L\{2\rho v(V_\infty - v)^2\}, \tag{11}$$

where: λ_L is the Lagrange multiplier. Hamiltonian is a function of v and r, so the Euler equation takes the form:

$$\frac{\partial H}{\partial v} - \frac{dH}{dr}\left(\frac{\partial H}{\partial\left(\frac{dv}{dr}\right)}\right) = 0. \tag{12}$$

TABLE 3 List of symbols.

Symbol	Meaning	Units
B	Number of blades	
c	Blade chord	m
C_D	Airfoil drag coefficient	
C_L	Airfoil lift coefficient	
D	Drag	N
$D = 2R$	Diameter of rotor	m
F	Tip Loss Factor by Prandtl	
h	Height	m
L	Lift	N
N	Power	W
P_x	Rotor trust	N
R	Rotor radius	m
v	Velocity	m/s
v_{ix}, v_{it}	Axial and tangential induced velocity components	m/s
v'	Displacement velocity	m/s
W	Resultant inflow velocity	m/s
x,y,z	Cartesian coordinate system	m
α	Angle of attack	rd
β	Blade setting angle	rd
$\varepsilon = C_D/C_L$	Inverted airfoil aerodynamic finnes	
φ	Iflow angle	rd
λ	Tip speed ratio	
λ_L	Lagrange's multplier	
$\xi = r/R$	Nondimensional radius	

Source: Own elaboration.

By inserting the Equations (11) to (12) we get:

$$\frac{\partial}{\partial v}[2\rho v(V_\infty - v) - \lambda_L\{2\rho v(V_\infty - v)^2\}] = 0. \quad (13)$$

From the above, we obtain a quadratic equation of the form:

$$3\lambda_L v^2 - (2 + 4V_\infty\lambda_L)v + \left(\lambda V_\infty^2 + V_\infty\right) = 0, \quad (14)$$

and hence:

$$v = \frac{1}{3\lambda_L}\{(1 + 2\lambda_L V_\infty) \pm \sqrt{\lambda_L{}^2 V_\infty{}^2 + \lambda_L V_\infty + 1}\}. \quad (15)$$

The dependence of the speed profile along the radius of the rotor depending on the height is represented by the formula, obtained by retaining two terms of Taylor series for the power velocity law:

$$V_\infty(h) = V_w\left(1 + r\frac{\alpha}{H}\cos\psi\right). \quad (16)$$

The Equation (15) allows to determine the value of v, as a function of the multiplier, which we get from the Equation (10) when the condition $N = N_0$ is full filed. In the general case, the analytical determination of is impossible. That is why Lagrange's multiplier should be calculated by the numeric way. The calculation algorithm is as follows:

1) assume $N = N_0$, select and specify the radius R, take the velocity profile $V_\infty(h)$ according to formula (16),
2) calculate v for which Equation (10) is satisfied,
3) calculate λ_L,
4) calculate v from formula (15).

2.3 | Data acquisition

The results of the calculations of the axial component of the induced velocity using the method presented above are presented below. Two wind turbines with different powers were selected for analysis:

With a power of 300 kW, rotor diameter $D = 32$m, and tower height $H = 50$m.

With a power of 2.3MW, rotor diameter $D = 70$m, and tower height $H = 100$m.

It was assumed that these power plants were in a place where the average annual wind speed, measured at a height of 10 m above ground level, is $Vw = 10$m/s. However, the following Hellman coefficients were used to determine the conditions determining the location: $\alpha = 0.19$, $\alpha = 0.17$, $\alpha = 0.245$.

3 | RESULTS AND DISCUSSION

Aligned with the research objectives of this scientific article, our analysis focused on exploring the relationships between variables. Specifically, the paper examines the connection between the wind farm's location (determined by the average annual wind speed and wind profile power law in the area) and its electricity generation capacity, as well as the geometry of the wind turbine blades. Subsequently, findings by conducting a case study involving a wind energy plants were verified. This comprehensive approach allowed to gain valuable insights and provide answers to the research questions posed in our study.

Figures 5–6 presents the variability of the axial velocity component induced along the rotor radius of each of the two analyzed power plants, comparing its distribution taking account off the vertical velocity profile and with $\alpha = 0.17$ and without taking this profile into account. The difference between the speed induced without considering the wind speed gradient and the maximum induced speed considering this gradient ranges from 9% to 11%.

The above analysis confirmed the assumption that include the vertical wind profile will have an impact on the geometry of the wind turbine blade. Therefore, further analyzes were started in accordance with the prepared design model described in Section 2.2.2.

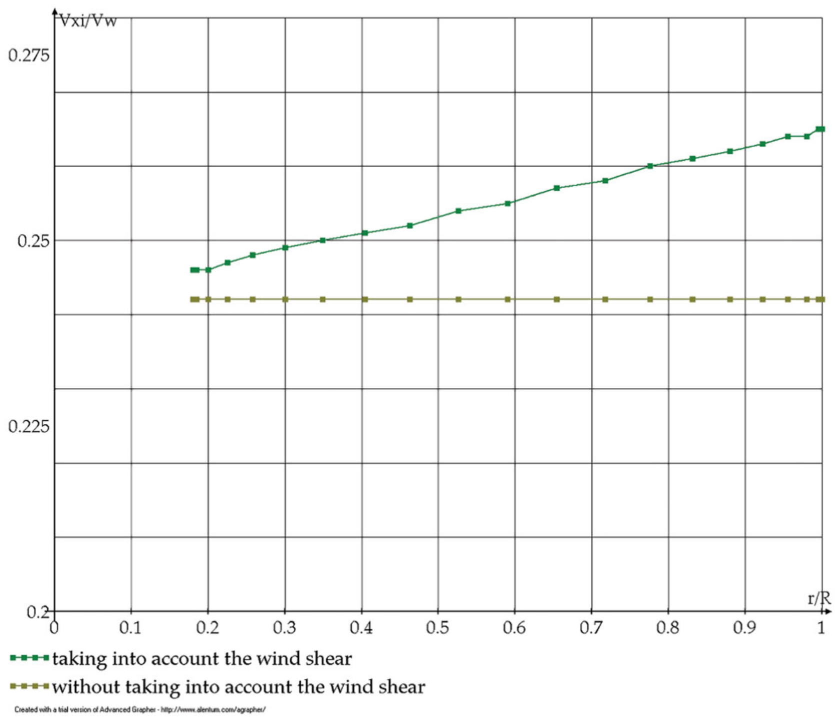

FIGURE 5 Distribution of the axial component of the induced velocity of the rotor radius for a 300-kW turbine. *Source*: Own elaboration.

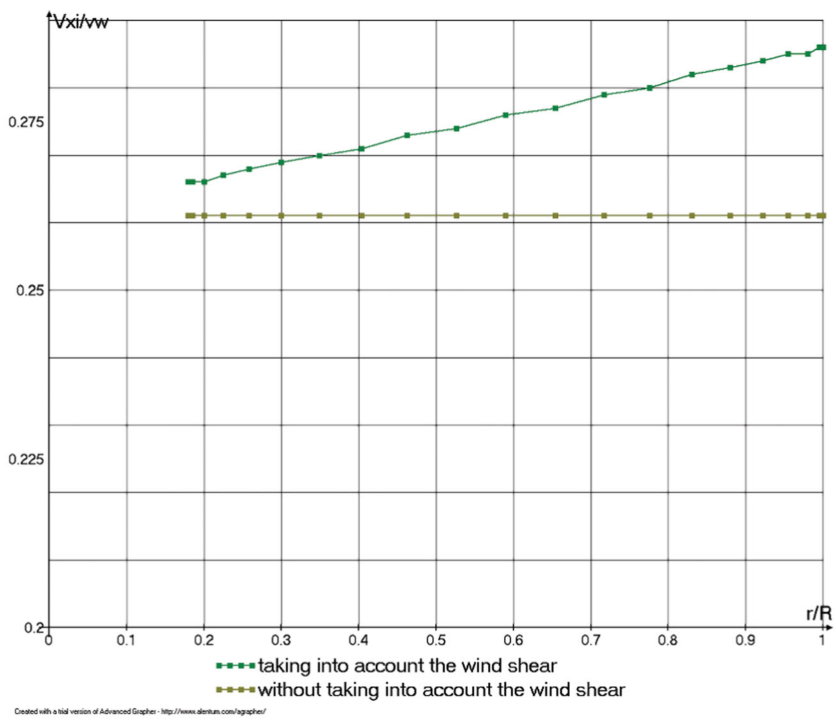

FIGURE 6 Distribution of the axial component of the induced velocity of the rotor radius for a 2.3 MW turbine. *Source*: Own elaboration.

The chord distributions calculated for the first turbine $P = 300\,\text{kW}$ are shown in Figure 7, where the blade outline obtained by this method was compared with the blade outline that did not consider the vertical wind speed profile.

A similar analysis was performed for the blade setting angle. Figure 8 presented the distribution of setting angles along the blade with and without considering the wind shear. In both analyses, significant differences in blade geometry are visible.

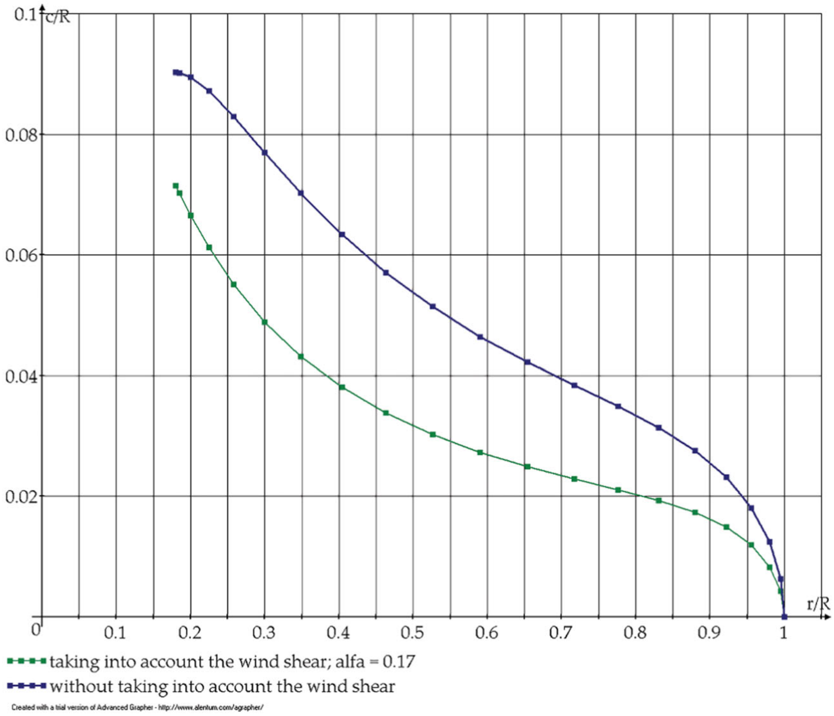

FIGURE 7 Chords distribution for 300 kW turbine with and without taking into account the wind shear. *Source*: Own elaboration.

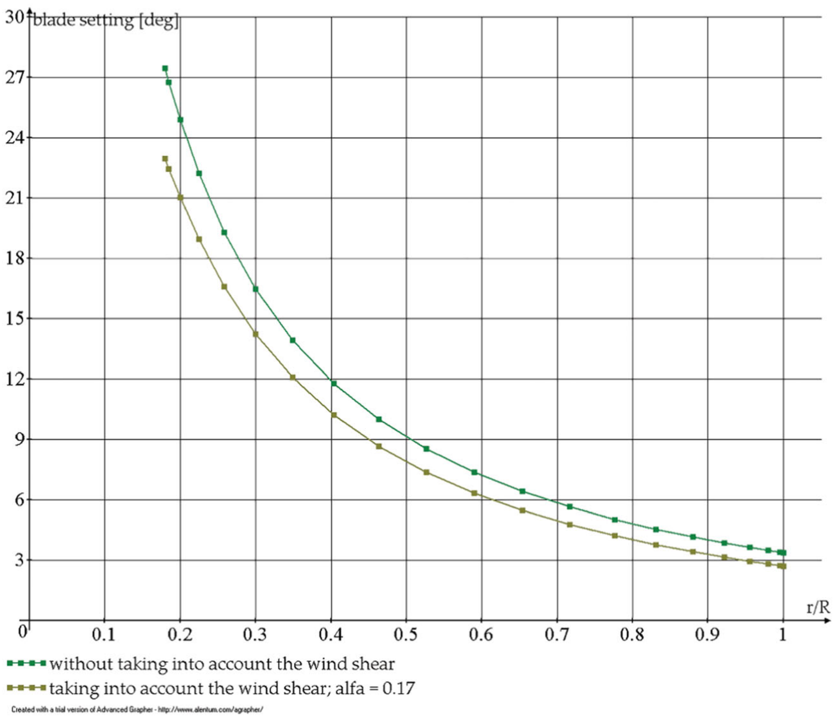

FIGURE 8 Blade setting angles distribution for 300 kW turbine with and without considering the wind shear. *Source*: Own elaboration.

In the previous considerations, the same coefficient α was adopted, that is, the same type of terrain.

Further analyzes attempt to answer the question of how the distribution of chords will change if the turbine is located in places with different terrain.

Figure 9 presents the chord distributions for various α coefficients for a 300 kW turbine. Similar dependencies on the influence of terrain roughness can be seen when comparing the blade setting angles. Figure 10 presents the blade setting distributions for various α coefficients for a 300 kW turbine.

Knowing the vertical wind speed profile, we know that wind speed increases with height, but graph flat becomes steeper with height. Therefore, the above

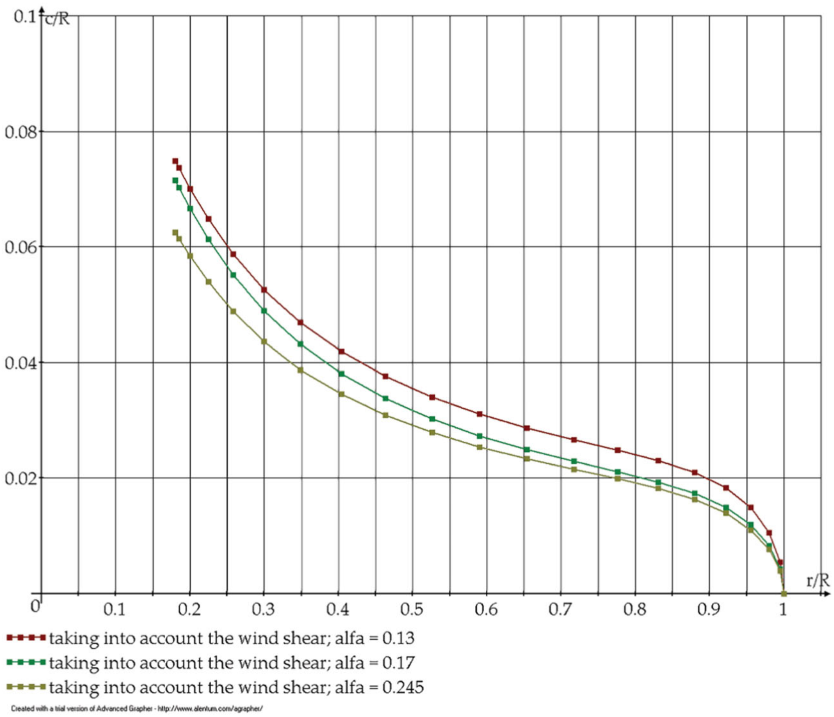

FIGURE 9 Chord distributions for a 300 kW turbine at different roughness coefficients. *Source*: Own elaboration.

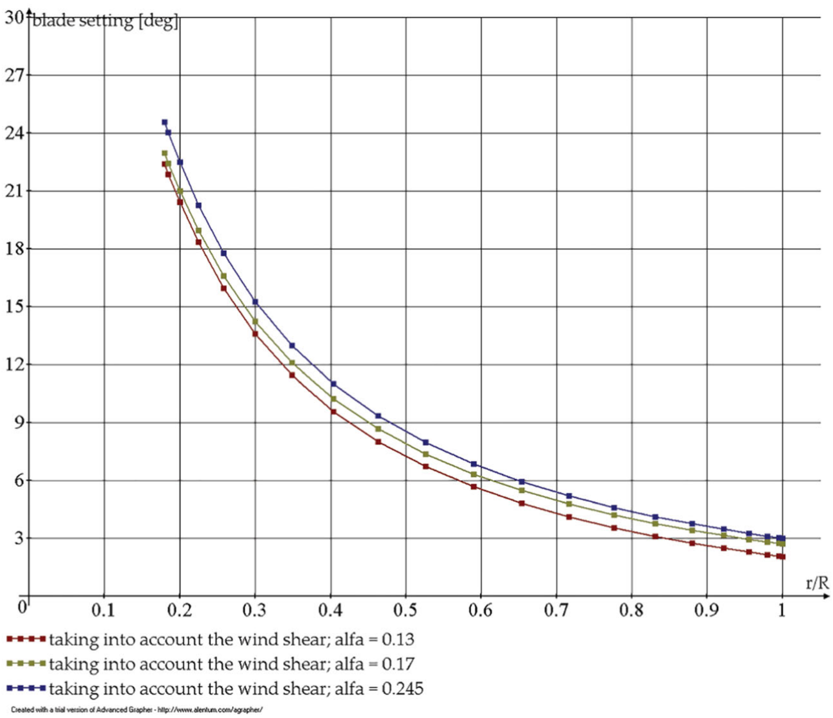

FIGURE 10 Blade setting angles distribution for 300 kW turbine at different roughness coefficients. *Source*: Own elaboration.

analysis was also performed for turbine with higher power and consequently a higher tower height.

Figure 11 presents the chord distributions for various α coefficients and Figure 12 presents the blade setting distributions for various α coefficients for a 2.3 MW turbine. It is worth noting that there is a small difference between the twist angle calculated without taking into account the vertical velocity profile and with it, compared to the large difference that occurred in the blade outline for this turbine comparing similar relationships.

The analysis revealed that, with a given vertical velocity profile, the chord distribution and blade twist

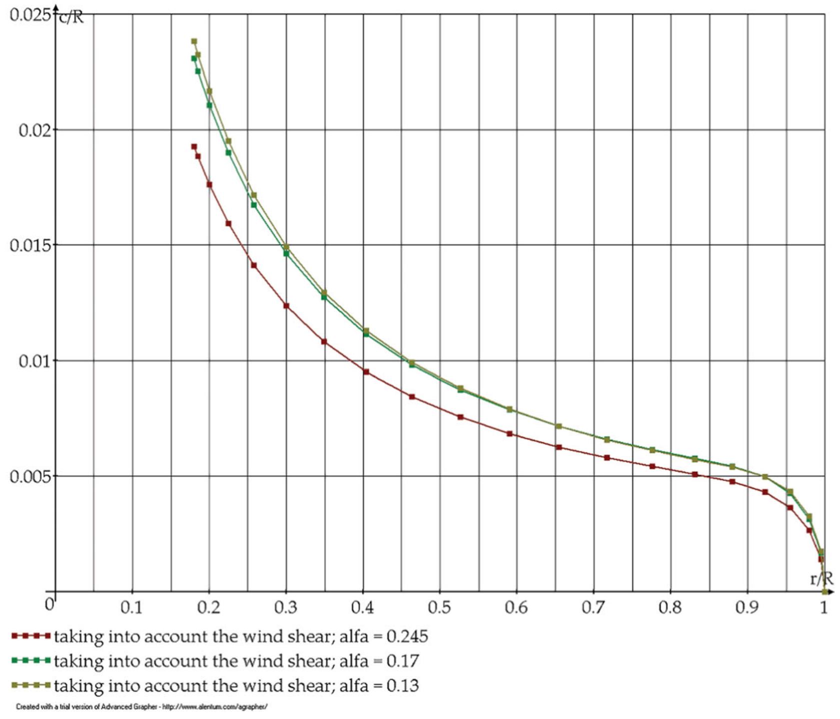

FIGURE 11 Chord distributions for a 2.3 MW turbine at different roughness coefficients. *Source*: Own elaboration.

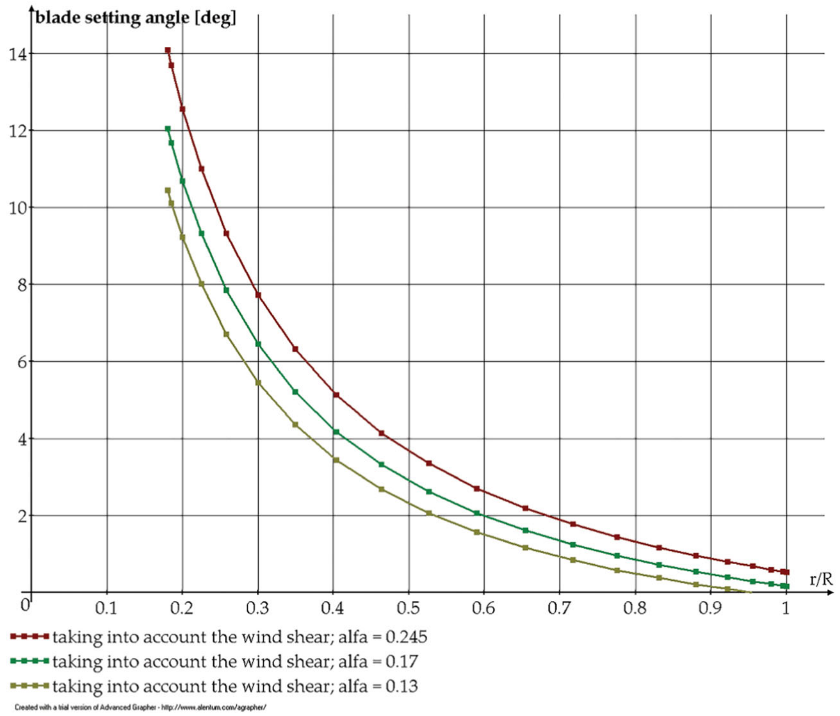

FIGURE 12 Blade setting angles distribution for a 2.3 MW turbine at different roughness coefficients. *Source*: Own elaboration.

angles change when the turbine is positioned in areas with different terrains. This underscores the profound impact of local wind and spatial conditions on blade geometry. The first question explored how wind shear affects the geometry of wind turbine blades, highlighting the existing gap in comprehensive analysis within the literature.[31–33] Upon examining the influence of wind profiles on wake displacement speed, the analysis strongly suggests the need for further investigation into the impact of wind profiles on blade geometry (Figures 5–6). The second question explored the relationship turbine location in various locations with differing terrain roughness and wind turbine blade geometry. This study confirmed notable differences in blade geometry for both 300 kW and 2.3 MW turbines (Figures 11–12).

Practically, these insights hold the potential to expedite the growth of the renewable energy sector, mitigate carbon emissions, and inform effective decision-making for wind energy projects. The conducted analyses and resulting insights can fortify effective investors' decision-making processes and inspire investments in wind-based electricity production technology. It is crucial to note that a wind farm situated in a location with varying wind conditions and terrain roughness will exhibit differing energy and economic indicators. This underscores the importance of meticulously considering these factors during the design, siting, and evaluation of wind energy projects.

For policymakers and sustainability advocates, newly developed with wind energy potential estimation approaches can enhance electricity generation capacity from wind turbine. It is crucial in establishing a sustainable energy system, especially amid climate change mitigation efforts, which require radical shifts in energy production methods. These shifts hinge upon identifying the optimal conditions for catalyzing transformative change.[53] Consequently, policymakers wield influence over energy policy formulation and, by extension, influence research priorities, thereby shaping the utilization of energy modeling-based outcomes.[54] This dynamic relation between energy modeling and decision-making processes showcases their reciprocal influence, as theoretical implications are drawn from practical contribution.

From the theoretical perspective, incorporating Weibull distribution and the wind profile power law to the considered analyses deliver a transparent and statistically robust approach to estimating profitability or capital cost projections for designing future power wind farms. In addition, the Weibull distribution, when combined with other methods such as those explored by Carrasco and colleagues,[55–57] allows for a sustainability assessment of wind energy. These combined methodologies serve as a foundational framework for further research. Furthermore, conducting an in-depth analysis of wind data and spatial conditions for the chosen site from a long-term perspective is advisable.

4 | CONCLUSIONS

The analysis presented in this study significantly advances our understanding of the relationship between local wind and spatial conditions and rotor geometry, thereby laying the groundwork for enhanced local investment in wind energy. The research used an original approach to the design of a wind turbine blade. The theoretical model used in design issues is based on a combination of the local momentum theorem and the use of the results of the propeller vortex theory.

Notably, this research addresses key questions regarding the impact of wind shear on blade geometry and the relationship between turbine location and blade design, shedding light on previously unexplored areas. These findings demonstrate that variations in terrain significantly influence blade geometry, highlighting the necessity for tailored turbine designs based on local conditions.

Moreover, the study reveals discrepancies in blade geometry across different turbine capacities and terrain types, offering novel insights into the optimization of wind turbine performance. These findings pave the way for future research endeavors aimed at further elucidating the intricate relationship between wind and spatial conditions and turbine geometry. By providing validated methods for optimizing turbine geometric parameters, the authors' research opens avenues for increased local investment in wind energy, thereby promoting distributed energy development and bolstering energy security. Future studies may explore the economic implications of optimizing blade geometry based on wind and spatial conditions, thereby driving improvements in wind turbine energy efficiency and sustainability.

In addition, further research avenues might include long-term wind data analysis and advanced turbine design using computational fluid dynamics. Additionally, prioritizing data-driven sustainability assessments can address environmental, economic, and technical concerns. Further investigations may explore various parameters such as turbine wake flow and time-series analysis under realistic conditions, enhancing our understanding of wind turbine performance.

In conclusion, countries like Poland face huge challenges in boosting renewable energy production, particularly wind energy.[58] European Commission initiatives, security concerns, and financial pressures due to rising energy prices underscore the urgency of wind energy development. This shift not only ensures energy security but also fosters job creation, and ecological modernization, offering local communities energy independence and decentralization opportunities.

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